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6. AUTHORS
Dryver Huston, Tian Xia

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Vermont
85 South Prospect Street, 340 Waterman Building

Burlington, VT 05405 -0160

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14. ABSTRACT
This project is an equipment acquisition contract under the U.S. Army Defense University Research Instrumentation Program (DURIP). The equipment acquired was a set of high-frequency and microwave instruments that configure into various test systems for ground and through-wall penetrating radars. This report is a description of the original proposal, equipment and components purchased, and some preliminary results from using the equipment.

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Report Title

Final Report: Adaptive and Cognitive Ground and Wall Penetrating Radar System

ABSTRACT

This project is an equipment acquisition contract under the U.S. Army Defense University Research Instrumentation Program (DURIP). The equipment acquired was a set of high-frequency and microwave instruments that configure into various test systems for ground and through-wall penetrating radars. This report is a description of the original proposal, equipment and components purchased, and some preliminary results from using the equipment.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
04/24/2015	4.00	Mohamed Metwally, Nicholai L'Esperance, Tian Xia. Compressive Sampling Coupled OFDM Technique for Testing Continuous Wave Radar, The Journal of Electronic Testing: Theory and Applications (JETTA), (12 2014): 75. doi: 10.1007/s10836-014-5501-5

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Huston D, Razinger J, Burns D, Xia T. (2015) "Phased Array and Nonlinear Ground Penetrating Radar Development" presented at SPIE Smart Structures/NDE Conference, San Diego, CA

Huston D, Burns D, Razinger J, Xia T. (2014) "Concrete Inspection with Phased Array and Nonlinear Penetrating Radar" presented at ASNT NDE/NDT for Highways and Bridges: Structural Materials Technology (SMT), Washington, DC

Huston D, Burns D, Venkatachalam A, Zhang Y, Xia T. (2014) "Microwave Concrete Assessment with Phased Array, Nonlinear and Waveform Sampling Methods" presented at ASCE Engineering Mechanics Conference, Hamilton, Ontario, Canada

Number of Presentations: 3.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received   Book

TOTAL:

Received   Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

None

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Mohamed Metwally	0.00	
Amr Ahmed	0.00	
Nicolai Lesperance	0.00	
Jonathan Razinger	0.00	
Yu Zhang	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Dylan Burns	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Dryver Huston	0.00	
Tian Xia	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Mohamed Metwally	
Amr Ahmed	
Jonathan Razinger	
Total Number:	**3**

Names of personnel receiving PHDs

NAME	
Total Number:	

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

None

Adaptive and Cognitive Ground and Wall Penetrating Radar

(Army DURIP)

Final Technical Report

August 5, 2013 to November 4, 2014

Contract Number: 000027484-W911NF-13-1-0301

Submitted by

Dryver Huston
School of Engineering
University of Vermont
Burlington, VT 05405

Tian Xia
School of Engineering
University of Vermont
Burlington, VT 05405

April 24, 2015

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2. List of Illustrations

3. Statement of the Problem Studied

3.1 Summary

This project is an equipment acquisition contract under the U.S. Army Defense University Research Instrumentation Program (DURIP). The equipment acquired was a set of high-frequency and microwave instruments that configure into various test systems for ground and through-wall penetrating radars. The following is a description of the original proposal, equipment and components purchased, and some preliminary results from using the equipment.

3.2 Proposal Overview

This proposal to DOD ARO DURIP is to purchase equipment that will assemble into an Adaptive and Cognitive Ground and Wall Penetrating Radar System (AC-GWPRS). The AC-GWPRS will enhance the ongoing high-frequency and microwave research and educational activities presently underway at the University of Vermont (UVM). The system comes in four main components: 1. A upgrade to add nonlinear analysis capabilities to an 13.5 GHz 4-channel Agilent AT-N5241A 10 MHz to 13.5 GHz PNA-X that is already being used in the laboratory at UVM. 2. A 15-bit 1.25 Gsps Arbitrary Wave Generator. 3. A 6 GHz RF Analog Signal Generator. 4. A 10-bit 2-8 GS/s High-speed Digitizer. The AC-GWPRS will serve three main purposes: 1. Serve as a system in support of fundamental research into adaptive and cognitive ground and through wall penetrating radar systems. 2. Serve as a testbed for applied problems that can benefit from adaptive and cognitive radar approaches, including the location and classification of buried objects, determining the structural characteristics of walls, and locating people behind walls and buried in debris. 3. Serve as an educational tool for graduate and undergraduate engineering students working in areas of microwave engineering, sensing, cognitive systems and structural identification. Students from Civil Engineering, Electrical Engineering, and Mechanical Engineering, and likely those from Materials Science will make use of this system in their studies and research.

3.3 Proposed Equipment Description

The plan is to acquire equipment that will assemble into an Adaptive and Cognitive Ground and Wall Penetrating Radar System (AC-GWPRS). The system comes in four main components: 1. A upgrade to add nonlinear analysis capabilities to an 13.5 GHz 4-channel Agilent AT-N5241A 10 MHz to 13.5 GHz PNA-X that is already being used in the laboratory at UVM. 2. A 15-bit 1.25 Gsps Arbitrary Wave Generator. 3. A 6 GHz RF Analog Signal Generator. 4. A 10-bit 2-8 GS/s High-speed Digitizer. The details are listed below. Quotes are attached in the Budget Justification. Additional funding for supplies in the amount of $6,000 are requested. The supplies will be used for the purchase of a controller PC, microwave cables, probes, absorbing foam and switches. The configuration of the system appears in Figure 1.

1. **AT-N5241AU N5241A Upgrades Nonlinear Vector Network Analyzer** – AT-N5241AU-010 Add Time Domain Operation $8,653.00; AT-N5241AU-510 Add Nonlinear Component Characterization $32,522.70; AT-N5241AU-514 Add Nonlinear X-Parameters $9,016.80; AT-

PS-S20-100 Productivity assistance, 2 days $4,821.20; AT-U9391C 26.5 GHz Comb Generator 2 $18,033.60; AT-E3620A Laboratory DC power supply $532.95; Subtotal $73,580.25

2. **AT-N8241A 15 bit Arbitrary Waveform Generator LXI Module** – AT-N8241A-016 16 M Sample Memory $6,949.60; AT-N8241A-125 1.25 Giga-samples per second sample rate $37,107.60; AT-N8241A-350 Function generator application$3,340.50; Subtotal $47,397.70

3. **AT-N5181B MXG X-Series RF Analog Signal Generator** – AT-1CP004A Rack mount flange $140.25; AT-N5181B-006 Instrument security removable memory card $1,354.05; AT-N5181B-303 Multifunction generator $1,405.05; AT-N5181B-320 Pulse train generator $1,756.10; AT-N5181B-506 Frequency range, 9 kHz to 6 GHz $17,493.00; AT-N5181B-UNT AM, FM, phase modulation $859.35; AT-N5181B-UNW Narrow pulse modulation $1,117.75; Subtotal $24,125.55

4. **U1056B Modular Multichannel Data Acquisition System** – U1065A 10-bit cPCI High-speed Digitizers, Acqiris; U1065A-004 Quad Channel, 2-8 GS/s, 256-1024 kpoints, $23,335.05; U1065A-F50 50 ohm, 2 GHz front-end $1,805.40; U1065A-128 128 Mpoint acquisition memory $3,034.50;U1092A-M13 Software and Drivers CD $0.00; R-51B-001-3C Return to Agilent Warranty - 3 years $827.70; U1091AK13 cPCI to PCIe interface, copper 5m $1,940.55; U1091AC30 3 slot CompactPCI 6U crate $2,799.05; R-51B-001-3C Return to Agilent Warranty - 3 years $106.75; U1092A-C02 6U blanking panel, XC200 $115.60; Subtotal $33,964.60

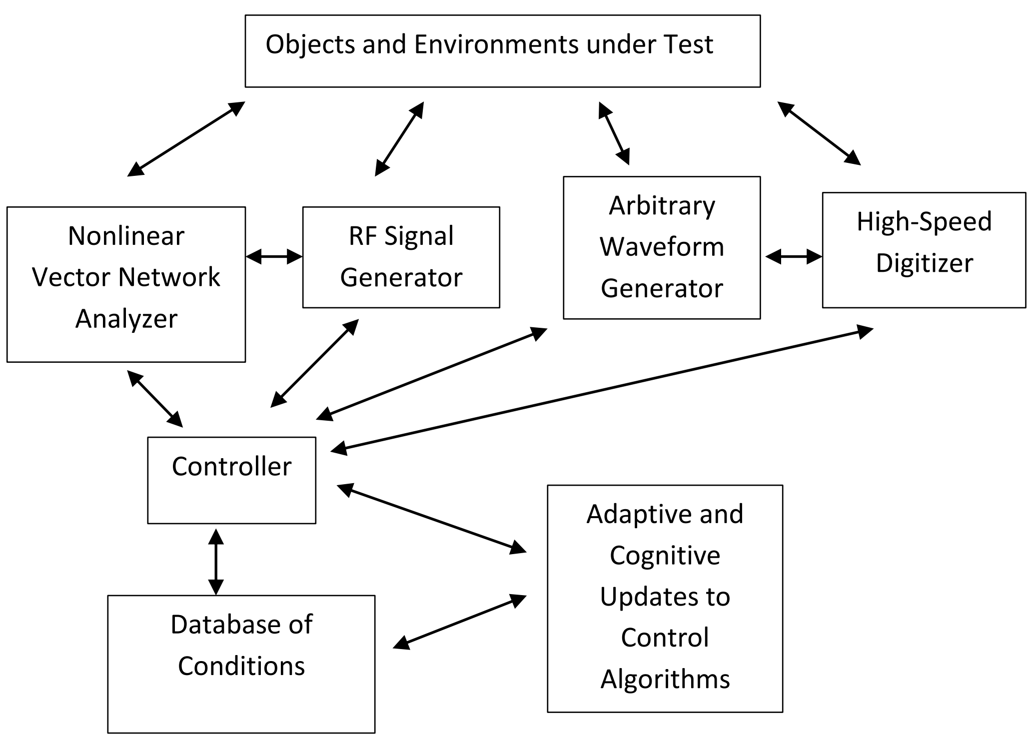


Figure 1 Configuration of Adaptive and Cognitive Ground and Wall Penetrating Radar System

This is a table top system and does not require any special circumstances for acquisition or installation. The useful life of this instrument (assuming it is not damaged or has an early life failure) is likely to be five to ten years.

3.4 Proposal Background

The objective of the proposed research is to study and develop adaptive and cognitive sensor systems with context aware system control and signal processing. The specific application is the agile operation of ground and wall penetrating radars for identification of subsurface objects, people, and structural conditions. In many respects the research questions are generic and apply to a variety of sophisticated sensor systems that operate in uncertain and complex situations where simple controls, such as threshold triggering, are inadequate. The cognitive radar concept was first introduced in a seminal paper by in 2006 by Haykin [2012] in which he made the analogy between the visual brain and radar, and proposed to develop intelligent radar with four fundamental functions that are basic to human cognition: 1. perception-action cycle; 2. memory; 3. attention; and 4. intelligence. The cognitive radar concept has spawned significant activity and interest, but the technology largely remains in its infancy.

Ground and Wall Penetrating Radar (GWPR) is firmly established as a set of techniques that provide nondestructive characterization for civil (highway infrastructure), geotechnical (buried utilities, storage tanks), geophysical (subsurface voids, saltwater intrusion), and defense (landmines, unexploded ordnance, structural condition for wall breaching) applications.

Ground and wall penetrating radar interactions with a bridge deck structure involve multiple physical effects. The primary interactions rely on the spatially-varying dielectric properties of structural material to reflect, scatter and absorb electromagnetic waves. Each of these interactions depends on the interplay of wavelength, polarization, and the geometric distribution of dielectric parameters. These complicated electromagnetic effects require GPR to function differently to detect and characterize different bridge deck subsurface defects of various electrical and physical properties. However in reality, operation of existing GWPRs is limited to the feedforward mode, where GPR transceiver functionalities are fixed and cannot be tuned to meet different inspection requirements. As a result, the efficacy of the measurement is not assured.

Adaptive and cognitive systems that control the test state of the system include control of the waveform frequency band, shape, phasing, pulse rate polarization and direction; antenna array beamforming; along with control of the acquisition gain, threshold, storage and detail of analysis. Figure 2 shows the concept.

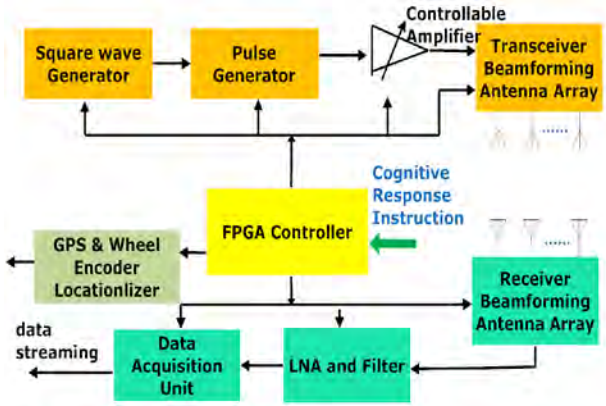


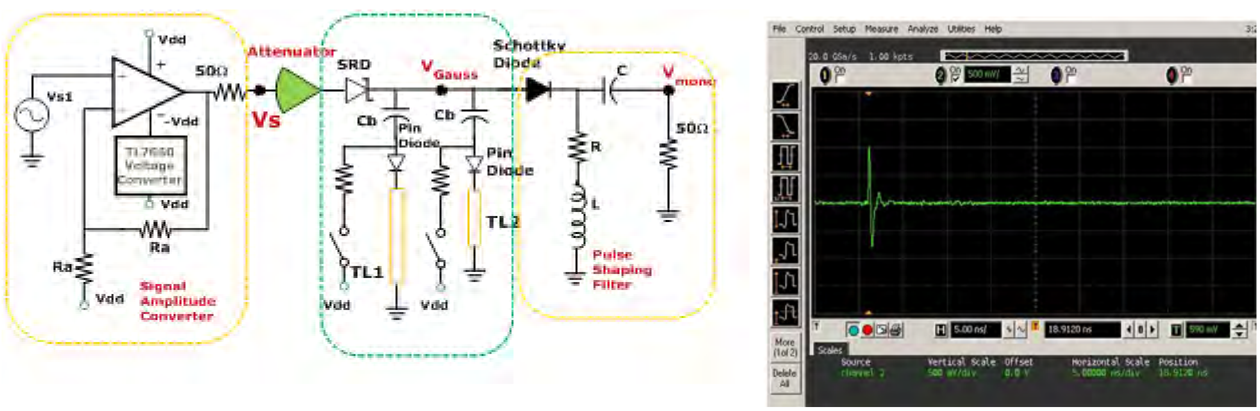
Figure 2 Adaptive GPR Transceiver Diagram

3.5 Proposed Projects

The following is a list of planned and possible projects that can make use of the AC-GWPRS.

3.5.1 Planned and Possible Project – Use of Programmable Pulse Generator

GPR signal penetration and deliverable longitudinal resolution is a tradeoff determined by radar operational frequency band. A low band signal penetrates the medium well, while a high band signal produces fine longitudinal resolution. The development of a programmable pulse generator can aid in this effort. Figure 3 a and b shows a prototype design developed at UVM. More agile designs are possible.



a.

b.

Figure 3 a. Programmable UWB pulse generator, and b. Gaussian monocycle pulse

3.5.2 Planned and Possible Project – Adaptive Antenna Array Beamforming

To obtain optimum inspections, different objects may require different observation angles. To achieve this, we will explore an antenna array beamforming technique to control antenna directivity and gain. Figure 4 illustrates our beamforming antenna array configuration, where antenna elements are selectable, and the input signal gain and phase delay of each antenna

element can be tuned digitally. Figure 5 shows some typical single channel data that we have collected. In order to properly control antenna array beamforming, we will conduct investigation in two steps: 1). Characterize the radiation pattern of each individual antenna element; 2). Characterize antenna array radiation patterns under different control codes. The characterization work will be conducted in an anechoic chamber assisted with HFSS electromagnetic simulations.

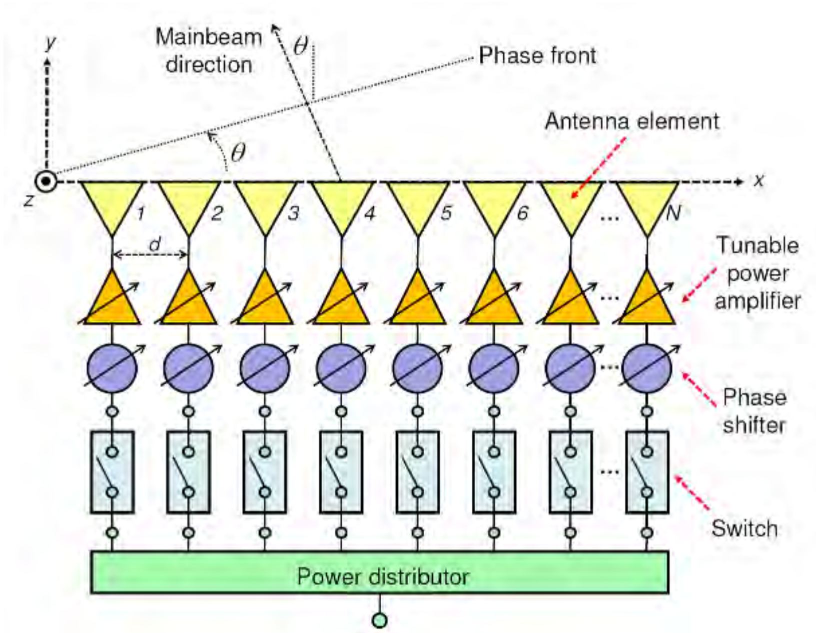
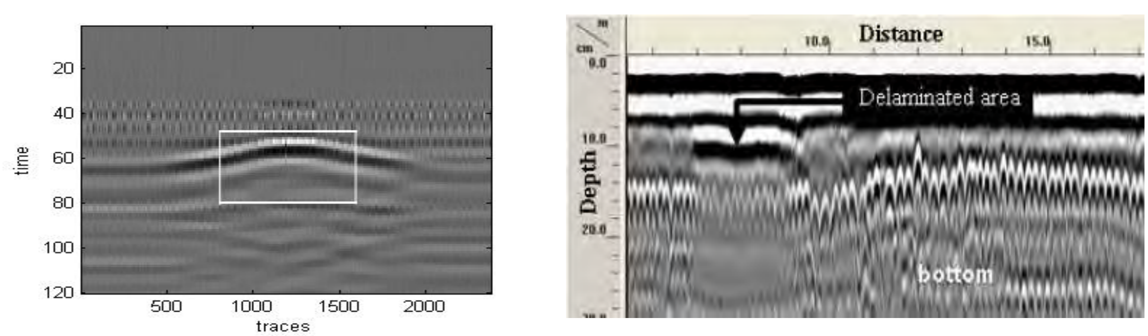


Figure 4 Beamforming Antenna Array



a. **b.**

Figure 5 a. Rebar hyperbola pattern, and b. Delamination image

3.5.3 Planned and Possible Project – Integration with GIS Database

A GIS database will be developed to construct the memory of the cognitive GPR system and will provide two functions: First, it will store geographical data, including subsurface features and their spatial information; thus, various geographic analyses can be performed to facilitate bridge maintenance efforts. Second, the database will save radar transceiver control parameters produced by the cognitive analyzer, and the electromagnetic waves' physical characteristics (frequency, amplitude, operational band, PRF etc.) and antenna array beamforming patterns associated with the inspection data vectors. Such information will be used as a-priori knowledge to direct the cognitive analyzer to dynamically adjust the transceiver circuit so as to facilitate comprehensive subsurface characterization and to optimize inspection performance.

3.5.4 Planned and Possible Project – Cognitive Control of GPR System

Using the cognitive information gathered from the real-time data analysis will provide information to the system controller for resetting the operational parameters to ensure optimal data collection performance. This portion of the research will be to examine the viability of various methods of exerting cognitive control over the system. At the heart of the controller is an optimal operational parameter-setting matrix that serves as a map from a discrete set of environmental (observational) condition states onto a discrete set of operational parameter states. Upon perceiving an environmental state, the controller uses the map to select the operational parameters. The process iterates as the system encounters new environmental state. A simple approach is to use an intelligent designer to preselect a static map. If the map is properly selected, this can be effective. Many situations are too complicated or unpredictable for a static preselected map. A more sophisticated, but possibly better, approach is to use machine learning to dynamically update the map. Updating methods include greedy and reinforcement techniques that alter the map in a positive response to parameters that improve performance [Bongard 2006] [Christenden 2010] and the motivational methods that attempt to reduce negative responses in a method analogous to pain avoidance [Starzyk, 2012]. All of these dynamic methods require a method to assess operational performance. In the case of cognitive GPR, the quality of the perceived data (dynamic range, depth of penetration, rebar clarity, etc.) is the likely best candidate for a performance metric. This research will include: 1. Determine suitable performance metrics. These have to be in a form that can be determined on a real-time basis. 2. Establish if the system can reliably switch states based on a static predetermined map. 3. Evaluate various machine learning algorithms for suitability in dynamically adjusting the map. Practical considerations including details specific to cognitive GPR will be considered. 4. Verify if dynamic control map setting is a viable technique for controlling a cognitive GPR system.

3.5.5 Planned and Possible Project – Adaptive Nonlinear Radar

Many of the testing and data processing techniques associated with using an linear vector network analyzer (LVNA) assume that the device, system or material is linear and responds to a harmonic input with a harmonic (sinusoid) at the same frequency as the input. Nonlinear and hysteretic effects can produce harmonic distortions in an output signal, even if the input is a pure single frequency harmonic.

Harmonic distortion frequency domain methods are a means of quantifying amplitude-dependent nonlinearities. The techniques attempt to use relatively simple models to describe behavior that extends beyond that of a linear system. Figure 6 shows the spectral behavior of a linear system subjected to a single-tone sinusoidal excitation. The response is a sinusoid at the same frequency, but with a possible amplitude and phase lag that depends on the excitation frequency. Figure 7 shows the spectral behavior of a nonlinear system with an amplitude dependent nonlinearity subjected to the same single-tone sinusoidal excitation. The nonlinearity produces harmonics at frequencies that are integer multiples of the fundamental. This result derives directly from using a sinusoid in a polynomial nonlinearity.

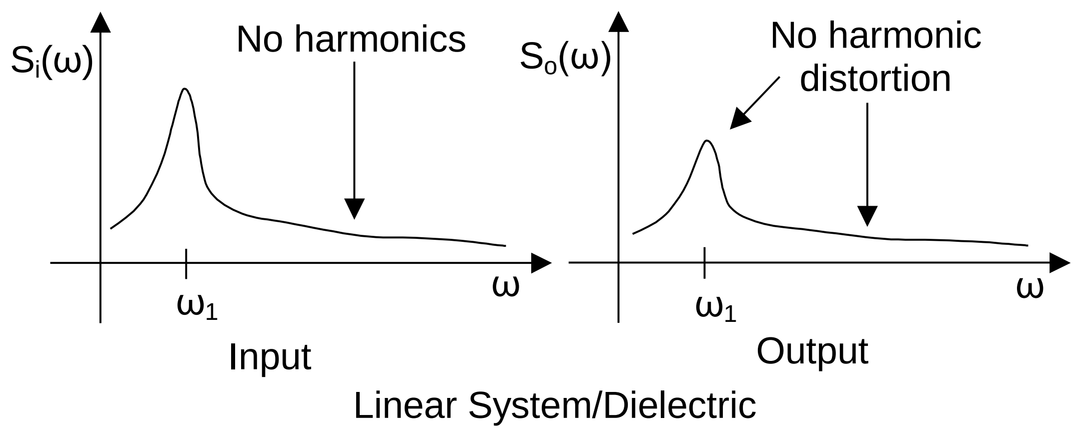


Figure 6 Linear system/dielectric with sinusoidal input produces sinusoidal output with no harmonics

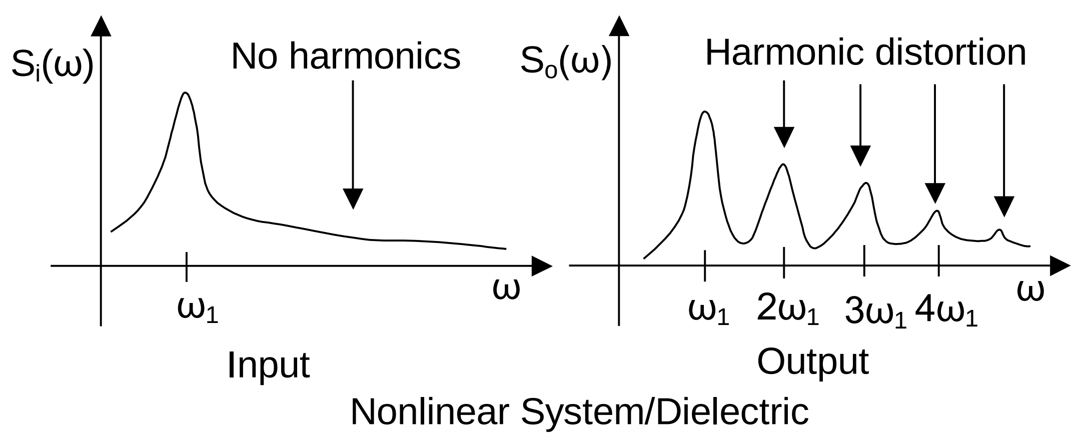


Figure 7 Nonlinear system with sinusoidal input produces output with multiple harmonics

Many, perhaps all, nonconductive materials exhibit some degree of dielectric nonlinearity. Some electroactive ceramics, such as ZnO, mixed in a polymer matrix are highly nonlinear [Zhou, 2001] [Kamiya, 2008]. A relatively simple form is an amplitude-dependent nonlinearity,

A Taylor series may provide an adequate representation of this type of nonlinearity [Morro, 1991]

$$\mathbf{D}(\omega) = \frac{\mathbf{E}}{|\mathbf{E}|}\varepsilon_0\left[\mathrm{a}_1(\omega)|\mathbf{E}| + \mathrm{a}_2(\omega)|\mathbf{E}|^2 + \mathrm{a}_3(\omega)|\mathbf{E}|^3 + ...\right] \tag{1}$$

The $a_i(\omega)$ coefficients are in general complex and frequency-dependent. Eq. (11) is a nonlinear generalization of linear frequency-dependent representations, such as (10). If there is symmetry with respect to the sign of E, then the even-index a_i should vanish. A truncated-series cubic nonlinear representation is

$$\mathbf{D}(\omega) = \frac{\mathbf{E}}{|\mathbf{E}|}\varepsilon_0\left[\mathrm{a}_1(\omega)|\mathbf{E}| + \mathrm{a}_3(\omega)|\mathbf{E}|^3\right] \tag{2}$$

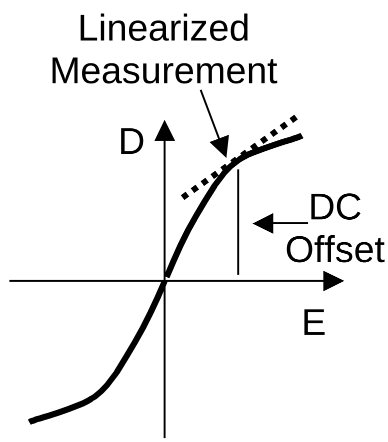


Figure 8 Nonlinear dielectric behavior with linearized measurement about DC offset

The polyharmonic distortion test methods are a class of techniques that apply a single or multiple sinusoids of various amplitudes as the test signals. Amplitude dependent nonlinearities convert the sinusoids into higher and mixed-order sinusoids with amplitudes and phases that depend on the nature of both the nonlinearity and the input signal. Harmonic distortion of single sinusoid input and intermodulation distortion (IMD) of a two-sinusoid input are common examples. Born et al. patented a method that quantifies the amount of corrosion in electrical interconnects by measuring the amount of harmonic distortion produced by the corroded junctions [Born, 2001]. Woodward and Kell used two-frequency IMD measurements to study the nonlinear dielectric behavior of collections of single-cell organisms [Woodward, 1991]. It was believed that the observed nonlinear behavior was due to the interactions of the electric fields with the cell membranes.

Similar to nonlinear dielectric testing, there has been a modest level of activity in developing and using nonlinear radar techniques for specialized sensing applications. Kwun et al. patented a system in 1993 for detecting corrosion in reinforcing bars buried underneath a concrete overlay by harmonic distortion and intermodulation distortion methods [Kwun, 1993]. It is

interesting to note that this system has not seen much, if any, use in concrete testing applications. One reason may be that the test instruments and data analysis techniques available at the time of invention were inadequate in terms of sensitivity and convenience for practical applications. Similarly Burkhardt and Kwun patented a system for using nonlinear harmonics to measure damage in protective coatings [Burkhardt, 2001]. As a student research project Aslam proposed an imaging radar operating at 1 GHz based on these techniques [Aslam, 2007].

In a nonstructural application Riley et al. developed a method to track the location of bees with small devices that responded to probing electromagnetic signals with a higher harmonic return signal [Riley, 1996]. The higher harmonic signal could be distinguished from the source signal. Another nonstructural application involves the use of nonlinear radar to detect buried electronic eavesdropping devices [Belyaev, 2003]. The operating principle is that the semiconductor components in the device are highly nonlinear and will readily radiate harmonics when excited with a suitable oscillating electromagnetic field.

3.5.6 Planned and Possible Project – Dual-Band Impulse Technology for Difficult Penetration Cases

Investigators at the University of Vermont have been developing GPR systems with advanced signal source and receive capabilities. These systems have been developed with the primary goal of building a system that can travel at highway speeds for roadway inspection, yet remain within the constraints of FCC 02-48 radiated electromagnetic emissions capability. Two of the main enabling technical features are full waveform digitization and dual-band ultrawideband source and receive capabilities. Full waveform digitization is a replacement of standard subsampling methods of data acquisition. It requires high speed digitization and high speed data pipelines. Full waveform digitization enables collecting GPR trace signals with a reduction in launched and received waveforms by factors up to 1000x. Full waveform digitization may be attractive for this system if reducing the radiated emissions is important for this system. Dual-band ultrawideband GPR uses impulse type electromagnetic waves for subsurface feature investigation. Figure 9 shows a steel fiber reinforced concrete test slab with GPR imaging.

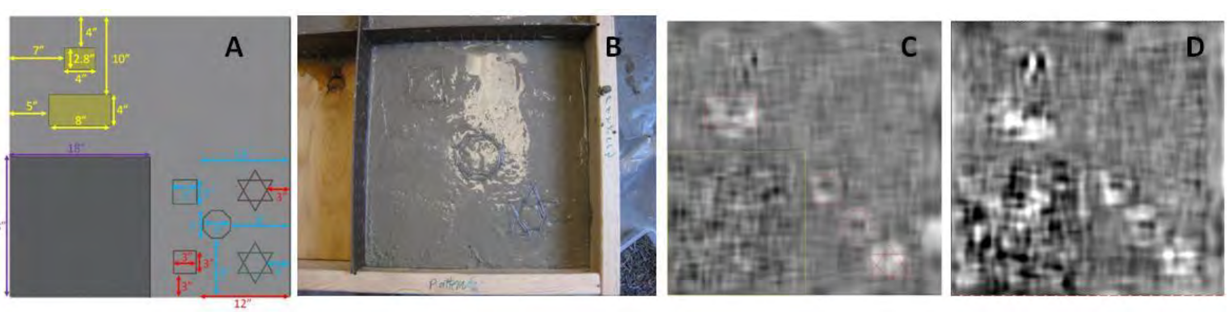


Figure 9 (A) Test slab design with physical feature layout. (B) Slab fabrication showing placement of finishing nail features. The finishing nails have length and diameter similar to those of common steel fiber reinforcing materials. (C) Map view of GPR data collected over the slab after 7 days of curing. (D) Map view after 17 days of curing. Decreased moisture content provides better resolution of structure features.

3.5.7 Planned and Possible Project – Frequency Agile Multi-standard Wireless Radio System

Progress in silicon integrated circuit technology and innovations in IC design have enabled the fast growing wireless communication products and services, like mobile phones, intelligent transportation systems, telemedicine, and wireless sensor network etc. The expanding growth of mobile products and services has led to various wireless communication standards, such as GSM, WCDMA, APCO 25, IEEE 802.11 WLAN, Bluetooth and ZigBee etc, which employ different spectrum bands and protocols to provide data, voice or video communication services.

It is highly desired to integrate various services to provide seamless global coverage, which includes global roaming across geographical regions, and interfacing with different systems and standards to provide seamless services at a specific location. Moreover, interoperability among different communication devices is greatly demanded by military and public safety agents to fluently exchange information in battlefield or incident/emergency. To achieve these features, mobile devices need to communicate and decode the signals using different air-interfaces. Furthermore, to manage changes in networking protocols, services, and environments, mobile devices should support multiple standards.

These pose important challenges to traditional wireless radio system design. Generally, the implementation of each communication standard requires a unique integrated circuit (IC) chipset. Since different standards are incompatible in terms of frequency band, date rate, modulation scheme and other specifications, conventional method is to stuff different chipsets, from RF front end to digital baseband into to a package, i.e. mobile handset, to support various standards. Nevertheless, this design method is gradually losing its effectiveness and feasibility: As many novel communication services and applications are emerging, the introduction rate of new communication standard will soon outstrip the circuit packing miniaturization rate. Simply stuffing different chipsets together will cause the integrated chip unfeasibly large, and the integrated circuit development cost will be prohibitively high.

In this research, we will explore new design methodologies to develop a flexible universal wireless radio platform that can operate across multiple wireless networks. Adaptive design technology will be pursued to build multifunctional circuitry that can be reconfigured to serve different standards to leverage design effectiveness and to accomplish integrated seamless global coverage, without having to squeeze multiple chipsets into a small package. The radio system will have intelligence to automatically monitor the RF environment and circuit specifications to adjust system to operate over multiple standards with optimum performance.

3.5.8 Planned and Possible Project – Non-Invasive Human Vital Sign Detection UWB Radar for Disaster Rescue Operations

In this research, we will explore ultra-wide band (UWB) ground penetrating radar (GPR) technology to develop an innovative non-invasive detection system that can remotely capture human vital signs, specifically respiratory movement and heart beat signals, for disaster rescue operations. Traditionally, GPR is used to characterize subsurface or hidden stationary subject by examining variations of reflection EM (electromagnetic) waveforms due to subject's distinct

dielectric parameters from the background. While for life-detection radar system proposed in this research, its operation mechanism is considerably different. Instead of checking the stationary object, life detection radar makes use of the Doppler-effect to monitor and capture dynamic vital signs of human body's movement. In the detection, the radar emits a narrow EM pulse beam to penetrate the rubble of collapsed buildings under which victims might be buried. When the living victim is illuminated by the microwave beam, the reflected wave will be modulated by the subject's body movements, specifically the respiration and the heartbeat. The modulation signal's frequency variation is proportional to the relative velocity of body movement to the radar transceiver. By characterizing the frequency variation, the buried victim can be detected and located. The development of this life-detection radar system consists of the following major elements: 1). UWB radar circuit that generates, amplifies, receives and filters various MW/RF signal components; 2). Small size antennas of high fidelity and sensitivity; 3). Signal processing method for low amplitude non-stationary human vital signs extraction and interference noise elimination.

3.6 Proposed Enhancement of the Quality of Research and Research-Related Education

A set of research projects and educational activities that make use of microwave frequency electronics are presently underway at the University of Vermont. These projects would definitely benefit from the addition of modern Nonlinear Vector Network Analyzer.

3.6.1 Projects Currently Funded by the DoD at Time of Proposal

One project presently being funded by the DoD that may directly benefit from the acquisition of the AC-GWPRS in this proposal. The project title is "UAV Sensing and Structural Technologies." The Principal Investigator is Prof. D. Huston (the PI on this DURIP proposal). The contract number is N00421-09-1-0008. The contract is with Naval Air Warfare Center Aircraft Division (NAWCAD), Attn: Charles Caposell, (Code 2.5.1.4.4), Bldg 441,29183 Bundy Road, Patuxent River, MD 20670-1161. This project has three main research components. The first is the development of automated noncontacting structural inspection using a noncontacting laser radar ultrasound approach, Figure 10. An intermittently pulsed YAG laser provides rapid nondamaging thermal heating at a point on the structure. A laser radar vibrometer picks up the resulting ultrasound vibrations. One of the key technologies to be developed is a laser radar vibrometer that operates on non-smooth surfaces. A promising technology being pursued is a laser Doppler method developed by US Army Research Lab in Adelphi, MD (Barry Stann is POC) [Redman, 2008]. The method uses incoherent laser pulses chirped in the 20 GHz range for Doppler velocimetry. Designing and debugging the laser radar signals would be enhanced with use of the AC-GWPRS. The second part is the development of coordinated self-healing and repair of wires, cables and structural panels [Huston, 2009] [Huston, 2011]. High-frequency signals (often mixed with time domain reflectometry analysis) can provide a good source of sensing wire and cable faults. It is possible that nonlinear effects will arise during material breakdown, such as arc-tracking. The AC-GWPRS would help with these high frequency measurements. The third piece is to develop active MEMs-based anti-vibration controllers for

avionics circuit boards [Huston, 2008]. This piece may benefit from using the AC-GWPRS if some of the higher frequency (MHz) vibrations exhibit nonlinear behavior.

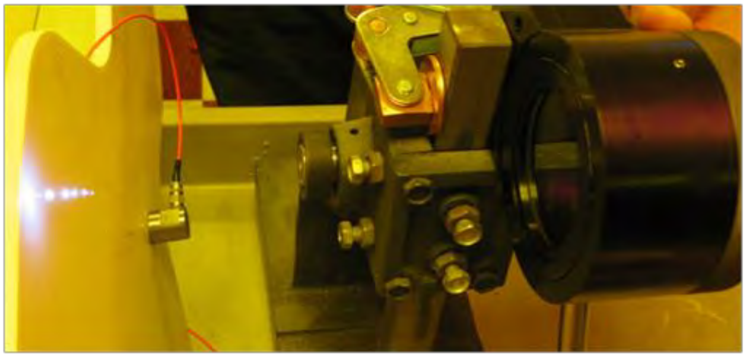


Figure 10 Polymer laser radar target outfitted with acoustic emission sensors

3.6.2 Proposed Establishment of New Research Capabilities and Enhancement of Current Research Capabilities for Performing Research and Research-Related Education in Areas of Interest to the DoD

Research is underway at the University of Vermont (with D. Huston as PI) on a set of projects related to various aspects in the use and development of ground penetrating radar systems. These projects are being funded by the Federal Highway Administration, US Department of Transportation and the National Institutes for Standards and Technology (with Northeastern University). Four lines of ground penetrating research are being pursued that would benefit from the use of an AC-GWPRS: 1. Shaped ultrawideband (UWB) pulse generation and processing – FCC regulations severely restrict the operation of UWB radars in the 1 to 3 GHz range. A mixer-based approach is being developed that produces a dual-band UWB source signal that avoids the 1 – GHz range by operating above and below this range, Figure 11. 2. Lidar-based vehicle position registration – The operation of ground penetrating radars at highway speeds requires the rapid and precise location of the vehicle relative to the roadway. Present GPS systems lack the speed and resolution required. Lidar techniques that fuse information with other sensors are being pursued as an option for high-speed and precision position registration, Figure 12. 3. Small antennas – Present ground penetrating radar antennas are bulky and inconvenient for traffic embedded roadway sensing. It would be useful if the antennas would be no larger than several centimeter. Electrically small antennas (sometimes called metamaterial antennas) are being examined as an option [Ziolkowski, 2009]. 4. Nonlinear radar for corrosion sensing – The harmonic distortion produced by corroded metallic structures may provide a disctinctive signature corresponding to corrosion. The goal is to develop a practical instrument that can identify, locate and possibly assess corrosion with nonlinear radar techniques. Figure 13 shows the use of a linear VNA in the prototype testing of a step frequency ground penetrating radar system.

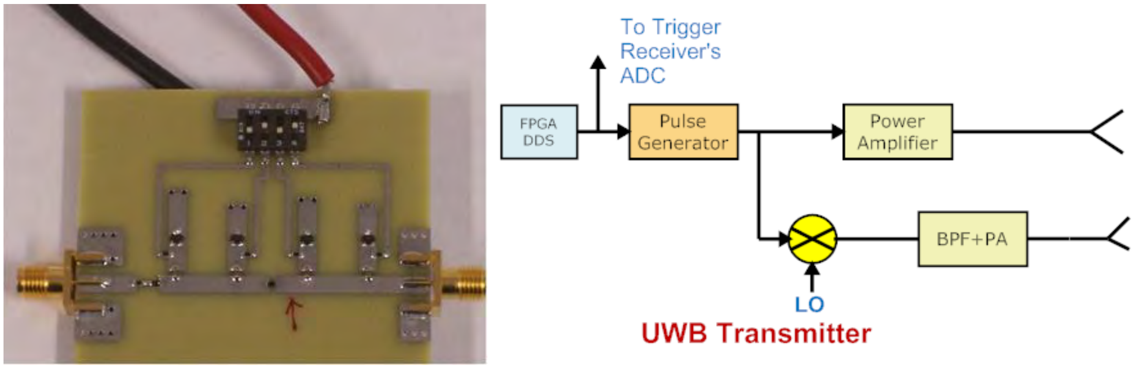


Figure 11 Stripline pulse generator and simplified mixer diagram for shaped UWB source

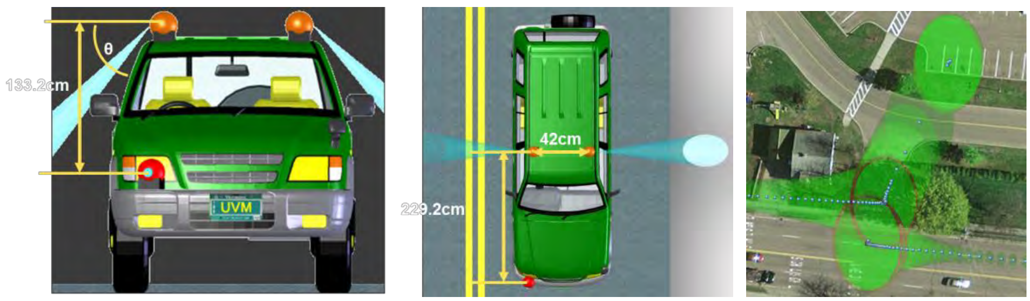


Figure 12 Cartoon of Lidar-based vehicle position registration and measurement of GPS tracking error

Figure 13 Use of linear vector network analyzer for penetrating radar scan of Turkey Lane Bridge deck (Hinesburg, VT, circa 2003)

Two future and somewhat speculative research efforts that may be pursued and aided with the acquisition of this equipment are nonlinear biosensing and active entangled photon radar. The concept behind the nonlinear biosensing is to the use the AC-GWPRS as a probe to measure the dielectric (preferably nonlinear) properties of biomaterials as they under various reactions, such as blood clotting. There are active research groups on the UVM campus that are willing to collaborate on this line of research. The active entangled photon radar concept centers around recent developments of this technology that use higher harmonic sensing as part of the physical

mechanism [Allen, 2008]. The AC-GWPRS could be an integral tool in examining the efficacy of this technique.

3.6.3 How the Proposed Instrumentation will Interface with Existing Facilities or Upgrade other Instrumentation Now Available for Research and Research-Related Education

The School of Engineering at the University of Vermont has laboratory facilities that would interface nicely with the proposed AC-GWPRS acquisition. This includes an 800 sq ft laboratory that is under direct control of the PI (Prof. D. Huston) for fabrication, setup and testing. This laboratory houses a variety of electronic test equipment including:

- Agilent AT-N5241A 10 MHz to 13.5 GHz PNA-X network analyzer
- Agilent Infinium 54854A 0 – 4 GHZ 8-bit digitizing oscilloscope.
- Agilent E4440A PSA Series Spectrum Analyzer (3 Hz – 26.5 GHz)
- HP 8753D 30 MHz to 6 GHz Network Analyzer
- Two A.H. Systems SAS-571 Double Ridge Guide Horn Antennas with a nominal frequency range of 700 MHz - 18 GHz.
- A.H. Systems SAS-510-2 Log Periodic Antenna with frequency range of 290 MHz - 2 GHz.
- A.H. Systems PAM-0118 Low Noise Preamplifier
- Picosecond Pulse Labs Pulse Generator Model 4015D, high frequency pulse generator with 12 ps transition time. Accessories include the following waveform shapers: PPL 5915-110-XGHZ Low-Pass Filter, PPL Model 5216 Impulse Forming Network,; and PPL Model 5510K attenuator.
- Agilent ADS software that includes X-parameter modeling capability.
- Olympus optical comparator
- HP 8753D 30 MHz to 6 GHz Network Analyzer
- Picosecond Pulse Labs Pulse Generator Model 4015D, high frequency pulse generator with 12 ps transition time. Accessories include the following waveform shapers: PPL 5915-110-XGHZ Low-Pass Filter, PPL Model 5216 Impulse Forming Network,; and PPL Model 5510K attenuator.
- Two Sick lidars
- DR-80 mobile robot
- Custom built dual-band GPR system with full waveform digitzation.

3.6.4 Proposed Staffing

The Principal Investigator on this project will be Prof. Dryver Huston of the School of Engineering at the University of Vermont. Dr. Huston has experience with the design and use of ground penetrating radar and other high-frequency electromagnetic measurements. Co-Investigator Assoc. Prof. Tian Xia, also of the UVM School of Engineering has expertise in high-speed electronic circuit design and measure.

3.6.5 Potential to Enhance the Institution's Ability to Educate, through the Research to be Conducted with the Proposed Equipment

There is an active graduate education effort underway at the University of Vermont where the research is making use of various aspects of high-frequency electronic instrument test and

design. The research would be significantly enhanced by the addition of a modern multipurpose high-frequency test instrument as with the proposed AC-GWPRS. The graduate students include 6 PhD and 3 MS candidates working in various modes on above-described projects. They include students pursuing degrees in Computer Science, Electrical Engineering, and Mechanical Engineering. Many of these graduate students are U.S. Citizens.

This research will also help to enhance and improve UVM microelectronics curriculum. The Co-PI Tian Xia teaches microelectronics courses at UVM, where students are instructed to design various computer and communication circuits for real life applications. Examples include software defined radio for security communication, spread spectrum clock generator for EMI reduction, clock jitter measurement circuit for production test and so on. Students have proposed and implemented novel designs that have led to prestigious journal and conference publications and patents. The responses from students have been overwhelmingly positive, as they enjoy being challenged with relevant, real-life problems. During the teaching practice, the Co-PI has received numerous inquiries and requests of radio frequency circuit designs, on account of its high demands by semiconductor and communication industry. Unfortunately RF design course is not offered in the current UVM microelectronics curriculum, which leaves a big gap between the industry demand and the academic education. Through this research, the Co-PI Tian Xia plans to create a RF circuit course to meet student requests. This new course will include state-of-the-art RF circuit design techniques, and integrate the research accomplishments arising out of this project. Students will study the theory and design methodologies of RF circuit components, such as various filters, amplifiers, oscillators, mixers and antennas etc. They will also learn how to integrate functional components to build complicate communication systems to meet systematic specifications. In order to help students gain practical knowledge and experience, Tian Xia will collaborate with local industry partners from IBM Microelectronics, and invite IBM engineers to act as student mentors to provide instructions on RF circuit design, test and analysis.

This research will also help to enhance and improve the UVM microelectronics curriculum. PI Tian Xia teaches microelectronics courses at UVM, where students are instructed to design various computer and communication circuits for real life applications. Examples include software defined radio for security communication, spread spectrum clock generator for EMI reduction, and clock jitter measurement circuit for production test. Students have proposed and implemented novel designs that have led to prestigious journal and conference publications and patents. The responses from students have been overwhelmingly positive, as they enjoy being challenged with relevant, real-life problems. While teaching, the PI has received numerous inquires and requests of radio frequency circuit designs, owing to high demand from the semiconductor and communication industry. Through this research, the PI plans to create a RF circuit course to address curricular needs. This new course will include state-of-the-art RF circuit design techniques, and integrates directly with the research activities. In order to help students gain practical knowledge and experience, the PI will collaborate with local industry partners from IBM Microelectronics, and invite IBM engineers to act as student mentors to provide instructions on RF circuit design, test and analysis.

3.6.6 Proposal References

Allen EH, Karageorgis M, Riga JM (2008) "Sensor Systems and Methods using Entangled Quantum Particles" US Patent 7,767,976

Aslam F. (2007) "Imaging with 1 GHz Harmonic Detector" Durham University School of Engineering Research Day 25.06.07

Belyaev V, Didkovskii LV, Mayunov AT, Razin'kov S. (2003) "Observation Characteristics of a Nonlinear Radar Subject to Noise Measurement Techniques" Vol. 46, 11

Bongard J, Zykov V, Lipson H. (2006) "Resilient Machines Through Continuous Self-Modeling" Science, Vol. 314, 17 Nov.

Born F, Dodge JE, Duff WG, Reynolds L, Turner, Jr. AG. (2001) "Apparatus and Method to Detect Corrosion in Metal Junctions" US Patent 6,275,050

Burkhardt G, Kwun H. (2001) "Nonlinear Harmonics Method and System for Measuring Degradation in Protective Coatings" US Patent 6,201,391

Christensen DJ, Schultz UP, Stoy K. (2010) "A Distributed Strategy for Gait Adaptation in Modular Robots" 2010 IEEE International Conference on Robotics and Automation Anchorage Convention District, May 3-8, 2010, Anchorage, Alaska, USA, pp 2765-2770

Haykin S. (2012) "Cognitive Dynamic Systems: Perception-action Cycle, Radar and Radio" Cambridge University Press (April 23, 2012)

Kwun H, Burkhardt GL, Fisher JL. (1993) "Detection of Reinforcing Steel Corrosion in Concrete Structures using Non-Linear Harmonic and Intermodulation Wave Generation" US Patent 5,180,969

Riley J, Smith AD, Reynolds DR, Edwards A, Osborne JL, Williams IH. (1996) "Tracking Bees with Harmonic Radar" Nature, Vol. 379, pp 29-30, Jan.

Starzyk JA, Graham JT, Raif P, Tan AH. (2012) "Motivated Learning for the Development of Autonomous Systems" Cognitive Systems Research 14, 10–25

Woodward A, Kell DB. (1991) "Dual-Frequency Excitation A Novel Method for Probing the Nonlinear Dielectric Properties of Biological Systems, and its Application to Suspensions of S. Cerevisiae" Bioelectrochemistry and Bioenergetics, Vol 25, 3, June, 395-413

Ziolkowski RW, Jin P, Nielsen JA, Tanielian MH, Holloway CL. (2009) "Experimental Verification of Z Antennas at UHF Frequencies" IEEE Antennas and Wireless Propagation Letters, Vol. 8

4. Summary of the Important Results

4.1 Equipment Acquired

The following lists the pieces of equipment that were acquired. The purchases largely followed that originally proposed. However, the Agilent Acquiris U1056B Modular Multichannel Data Acquisition System was not acquired and instead a dual-band 1.6 GHz and 500 MHz controllable ground penetrating radar was acquired. The reason for this change was that addition high-speed digitization options became available during the course of this project and the dual-band GPR system offered the opportunity to perform cognitive GPR research.

4.1.1 AT-N5241AU Nonlinear Vector Network Analyzer Upgrades

The Agilent PNA-X 13.5 GHz 4-Channel Vector Network Analyzer already in place in our laboratory was upgraded to have nonlinear capabilities, largely through a combination of firmware upgrades and the addition of supporting hardware, Figure 14. The firmware upgrades ($55,244.14) were:

1. *AT-N5241AU-010 Add Time Domain Operation* – This enables easy conversion between time a frequency domain for analysis of the measured signals.

2. *AT-N5241AU-510 Add Nonlinear Component Characterization* – This enables measurement of nonlinear properties of components, largely through harmonic distortion methods.

3. *KT-N5241AU-087 Add Intermodulation Distortion Measurements* – This enables measurement of multitoned intermodulation products in nonlinear component testing.

4. *AT-N5241AU-514 Add Nonlinear X Parameters* – This enables the calculation of X-parameters from the nonlinear component measurements.

The hardware upgrades consisted of:

1. *2 AT-U9391C 26.5 GHz Comb Generators* ($18,394.98), Figure 15 – The comb generators provide multifrequency reference signals for nonlinear harmonic testing.

2. *AT-E3620A Laboratory DC power supply, 0-25 V, 0-1A 1* ($558.45), Figure 16 – This supply provides power to the comb generators.

3. *KT-U2000A USB Microwave Power Sensor, 10MHz- 18GHz* ($3,360.90), Figure 17 –This power sensor enables calibration of the network analyzer.

4. *AT-N5181B MXG X-Series RF Analog Signal Generator 6 GHz* ($24,614.30), Figure 18 – This provides source signals for the nonlinear testing and also serves as a standalone source for microwave testing.

5. *Electro-Metrics EM-6992 Electromagnetic Probe Set 1 GHz* ($5,091.50) Figure 19 – This allows for measurements of electromagnetic fields, mostly in the near field.

6. *A.H. Systems Double Ridge Guide Horn Antenna SAS-571 700 MHz - 18 GHz* ($3,486.11) – This antenna enables additional ultrawideband field measurements.

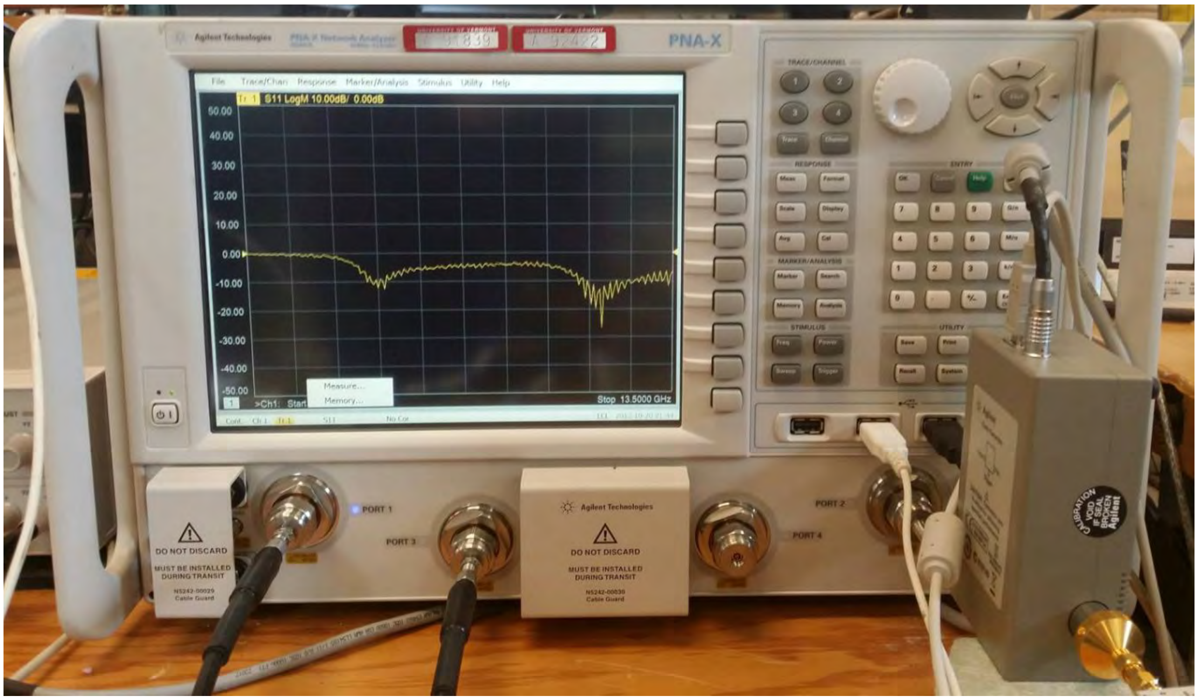


Figure 14 Agilent PNA-X 13.5 GHz 4-Channel nonlinear network analyzer

Figure 15 Agilent N10149 26.5 GHz Comb Generator

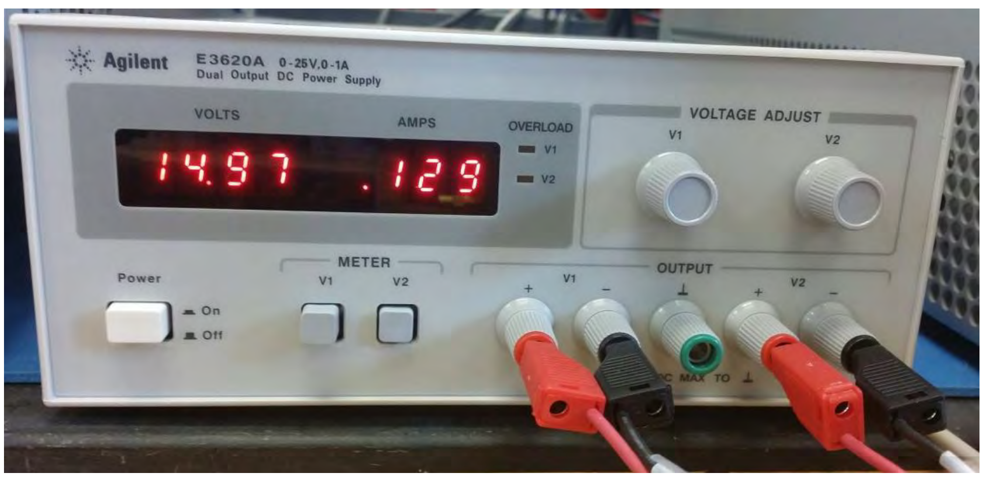


Figure 16 AT-E3620A Laboratory DC power supply, 0-25 V, 0-1A

Figure 17 KT-U2000A USB Microwave Power Sensor, 10MHz- 18GHz

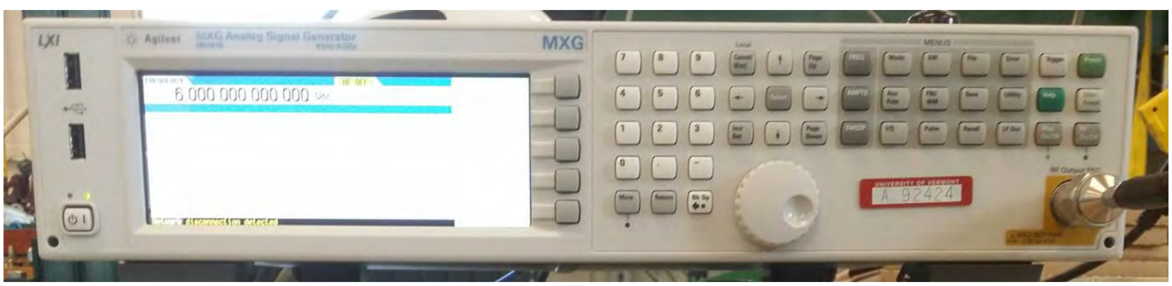


Figure 18 AT-N5181B MXG X-Series RF Analog Signal Generator 6 GHz

Figure 19 Electro-Metrics EM-6992 Electromagnetic Probe Set

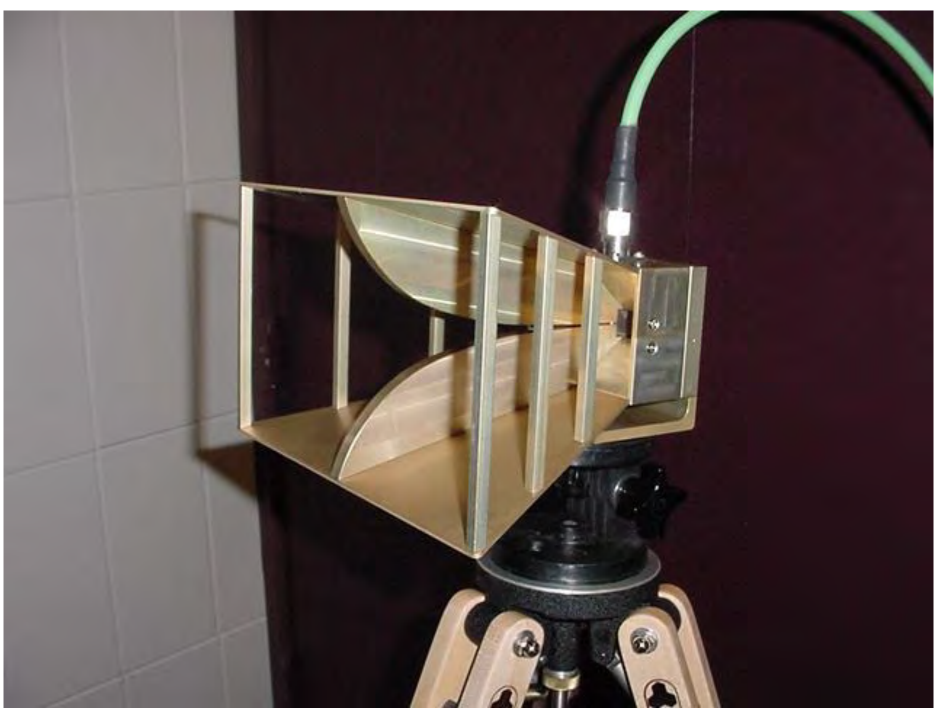


Figure 20 A.H. Systems Double Ridge Guide Horn Antenna SAS-571 700 MHz - 18 GHz

4.1.2 Arbitrary Waveform Generator

An *At-N8241A 15 bit 1.25 GHz Arbitrary Waveform Generator with LXI Module* ($ 47,765.13) was acquired, Figure 21. This instrument provides arbitrary waveforms for controlled microwave source experiments.

Figure 21 AT-N8241A 15 bit 1.25 GHz Arbitrary Waveform Generator with LXI Module

4.1.3 Dual-Band Ground Penetrating Radar

A *Geophysical Survey Systems SIR 30 Dual Channel Ground Penetrating Radar System with 400 MHz and 1600 MHz channels* ($19,154.50) was acquired with the total costs split with a Vermont Agency of Transportation research contract. This system was assembled onto an existing Mala Roadcart, as a modification. The system enables measuring with the dual bands under control, and is intended to serve as a test bed for cognitive ground penetrating radar concepts.

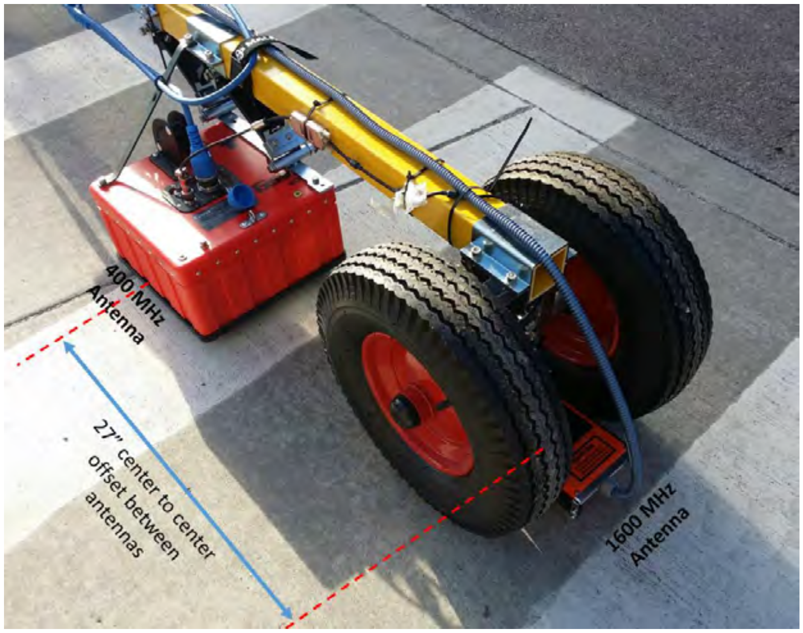


Figure 22 Geophysical Survey Systems SIR 30 Dual-Band Ground Penetrating Radar System with 400 MHz and 1600 MHz channels custom mounted onto a MALA Roadcart

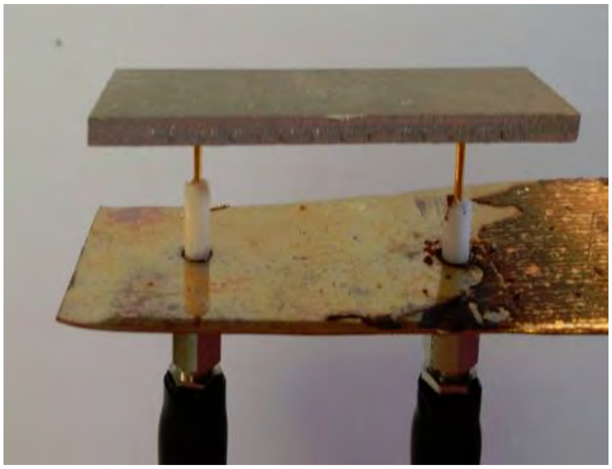
4.2. Results to Date from Use of the Equipment

4.2.1 Harmonic Distortion Corrosion Measurements

Experiments were setup using the nonlinear vector network analyzer to see if the presence of corrosion and different metals would lead to measurable differences in harmonic distortion in the microwave frequency range. Several different tests fixtures were initially tried, and largely inconclusive. Sometimes the results seemed promising, other times they were contradictory. A significant improve occurs if the network analyzer is recalibrated using the power meter before every test. Nonetheless, it is difficult to produce signals large enough to induce nonlinear effects in the test object without introduces nonlinearities from the test fixture. Some results appear below. Figure 23 shows a ground plane test fixture configuration with a. clean steel, b. corroded steel and c. aluminum test samples. Figure 24 shows the harmonic distortion amplitudes of a 1 GHz fundamental with somewhat minor differences. Figure 25 shows the harmonic distortion phases of a 1 GHz fundamental. The phase differences are noticeable.

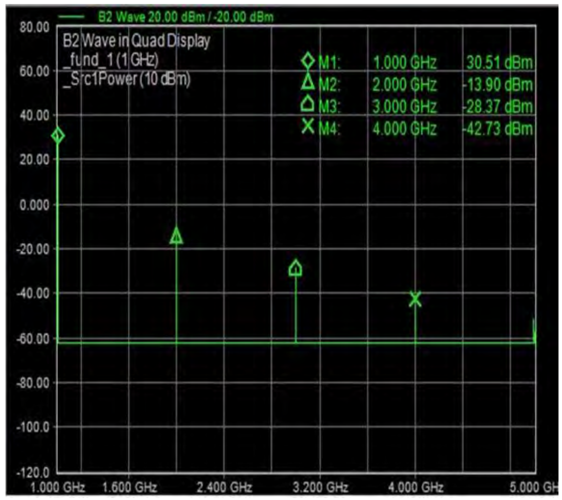
a. Clean steel

b. Corroded steel

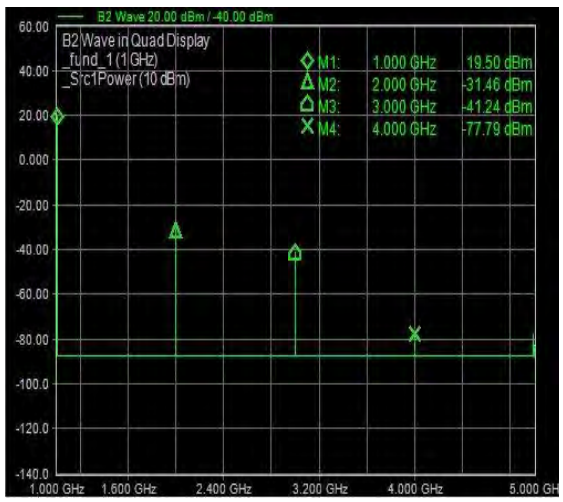


c. Aluminum

Figure 23 Different metals in ground plane harmonic test mount



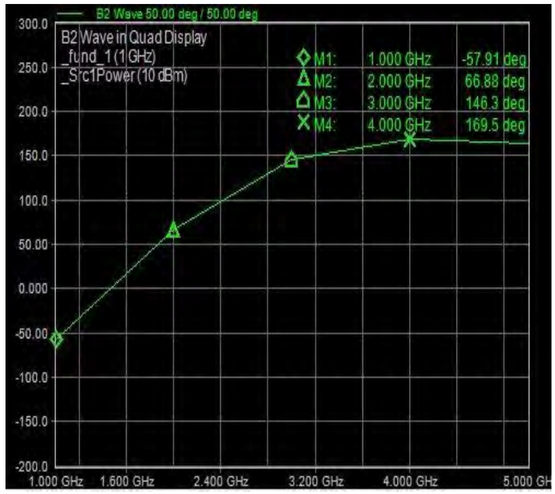
a. Clean steel



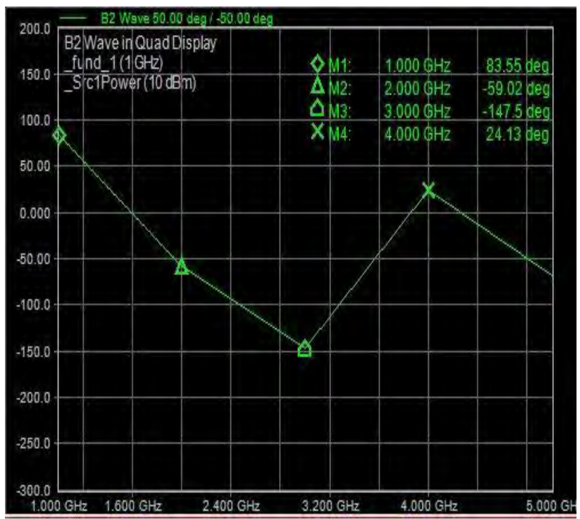
b. Corroded steel

c. Aluminum

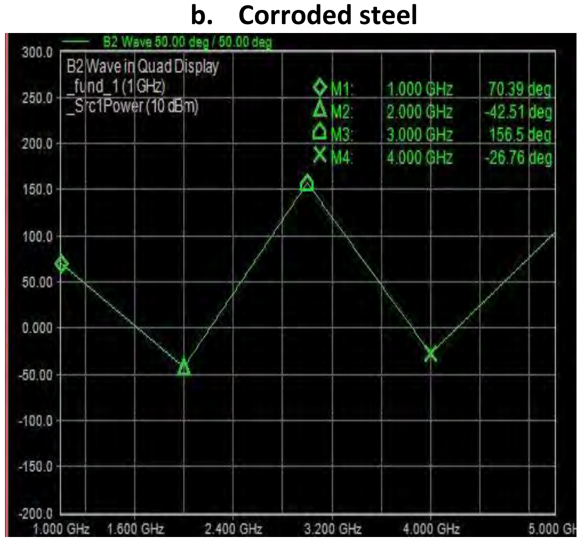
Figure 24 Harmonic distortion amplitudes of different metals with 1 GHz fundamental: a. clean steel, b. corroded steel, and c. aluminum



a. Clean steel



b. Corroded steel



c. Aluminum

Figure 25 Harmonic distortion phases of different metals with 1 GHz fundamental: a. clean steel, b. corroded steel, and c. aluminum

4.2.2 Design and Testing of UWB Antenna for Air Coupled Impulse Ground Penetrating Radar Applications

This research focused on a new TEM flared horn antenna for the demanding requirement of an air coupled impulse ground penetrating radar (GPR), Figure 26. Design goals include achieving good impedance matching throughout the wide frequency band while minimizing size. The design procedure included constructing an analytic model to evaluate the preliminary physical dimensions to achieve minimum reflections, followed by structural fine tuning for performance optimization. Experiments conducted using equipment bought in this project (Agilent PNA-X 13.5 GHz 4-Channel nonlinear network analyzer, AT-N5181B MXG X-Series RF Analog Signal Generator 6 GHz, Electro-Metrics EM-6992 Electromagnetic Probe Set, and A.H. Systems Double Ridge Guide Horn Antenna SAS-571 700 MHz - 18 GHz) validated the design effectiveness. Figure 27 shows the calculated antenna radiation pattern. Figure 28 shows the radiation pattern measurement setup. Figure 29 and Figure 30 show typical radiation pattern measurements. Figure 31 shows one of the antennas and a head-to-head transmission measurement setup. Figure 32 shows a launched pulse shape. Figure 33 shows a received pulse using two of the new antennas, and Figure 34 shows a pulse received from an A.H. Systems Double Ridge Guide Horn Antenna SAS-571 700 MHz - 18 GHz ultrawideband antenna. The new antenna has a better low frequency performance and has less ringing in the received signal.

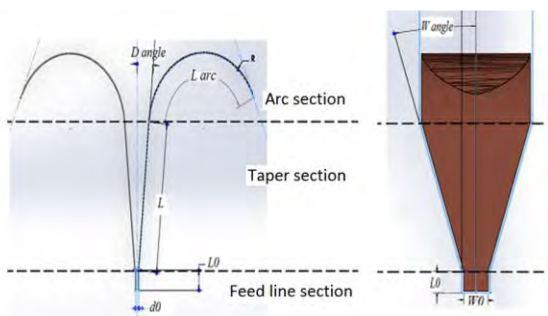


Figure 26 Top view and side view of proposed horn antenna

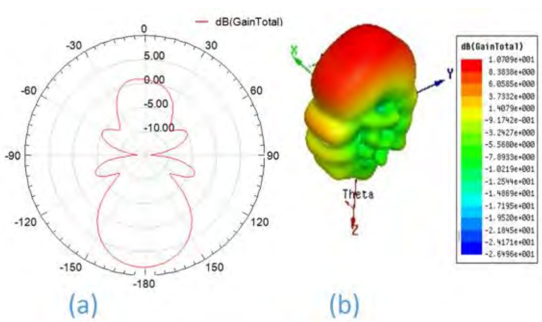


Figure 27 Antenna radiation pattern calculated with HFSS

Figure 28 Radiation pattern measurement setup

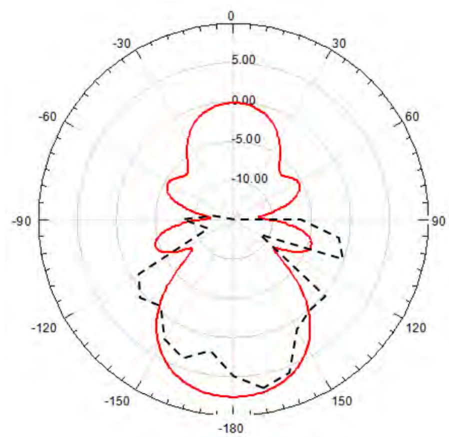


Figure 29 Measured (dashed) versus simulation (solid) radiation pattern at 1.9 GHz

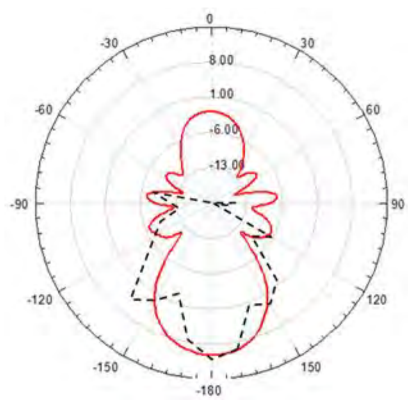


Figure 30 Measured (dashed) versus simulation (solid) radiation pattern at 2.8GHz

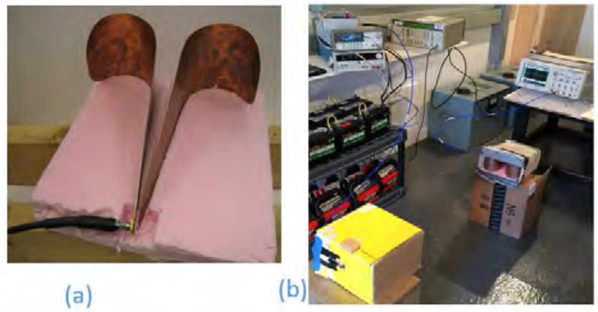


Figure 31 (a) the fabricated antenna (b) direct pulse signals transmit and receive setup

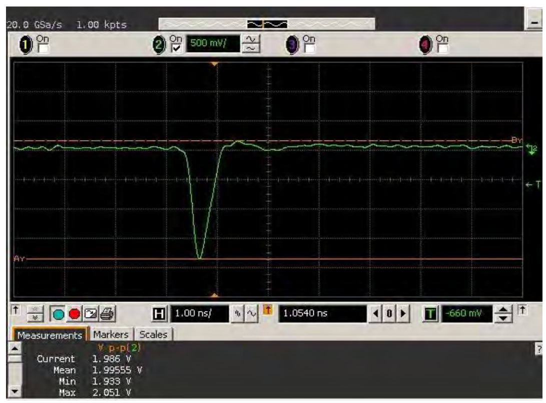


Figure 32 Generated pulse signal (-20 dB attenuation for measurement convenience)

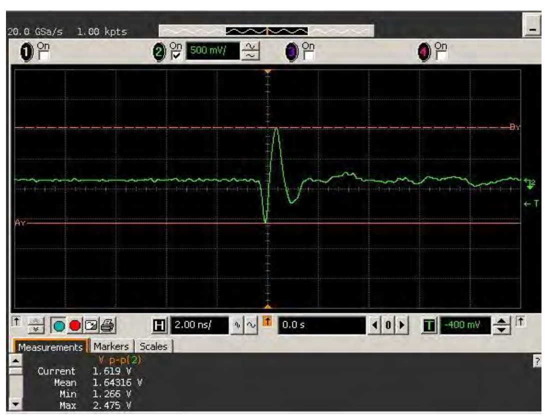


Figure 33 Received pulse signal with our antennas

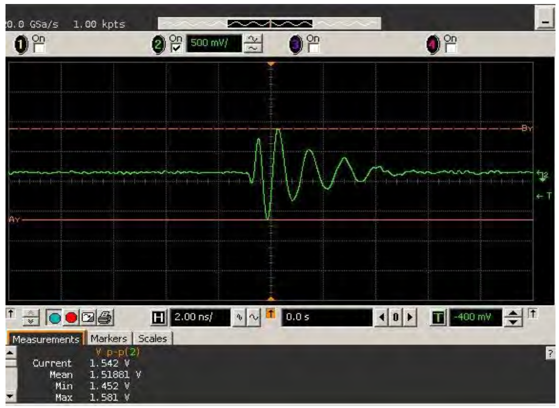


Figure 34 Received pulse signal with A.H. Horn Antennas with increased level of ringing

4.2.3 Waveform Sampling ASIC

Digitizing microwave signals requires a high-speed ADC. Waveform Sampling Application Specific Integrated Circuits (WFS-ASIC) are a potentially low-cost method of digitizing high channel count systems with repeated low duty cycle waveforms. The primary development path of WFS-ASICs is in the field of high-energy physics where particle accelerators produce intermittent high-frequency (GHz) signals with cycle repetition frequencies in the tens to hundreds of kHz. These signals are similar to those used in ultrawideband radar, particularly impulse ground penetrating radars. A WFS-ASIC evaluation board (PSEC-4) was provided by the University of Chicago Physics Department (H. Frisch and H. Oberla), Figure 35. This board uses a bank of analog sample and hold circuits to capture high-frequency signals in time-domain discrete and amplitude analog form, followed by amplitude digitization with a lowerfrequency and lower cost digitizer.

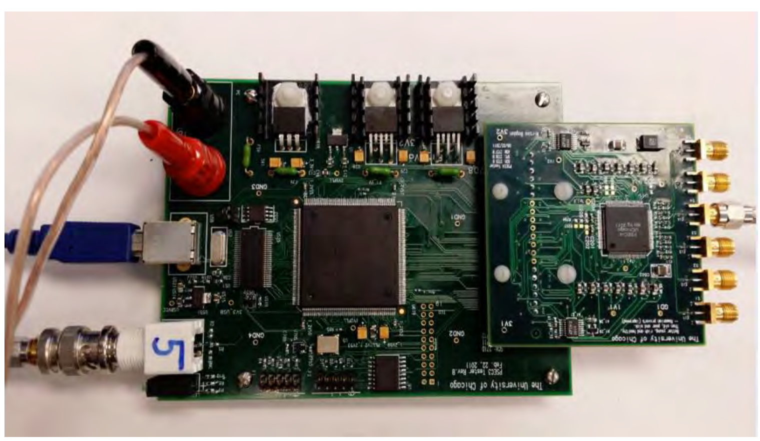
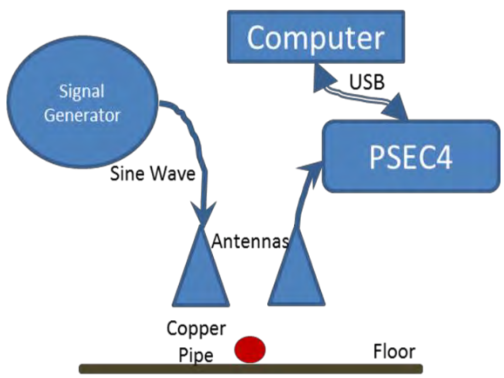


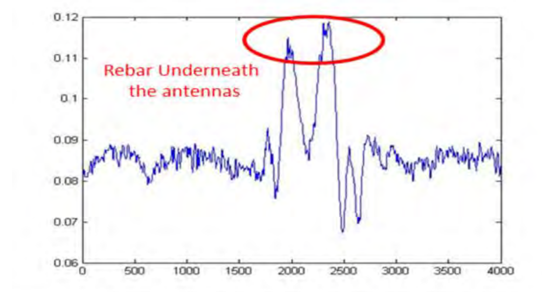
Figure 35 PSEC-4 Waveform Sampling ASIC, 6-channel input, 12-bit ADC at 10 GSPS (System developed by H. Frisch and E. Oberla, University of Chicago)

A series of experiments have been undertaken initially to establish the capabilities and range of operation of the PSEC-4 WFS-ASIC and then to begin to examine some novel forms of GPR, in particular multi-antenna simultaneous launch and receive methods. These tests used the AT-N5181B MXG X-Series RF Analog Signal Generator 6 GHz and the A.H. Systems Double Ridge Guide Horn Antenna SAS-571 700 MHz - 18 GHz. Figure 36.a shows the experimental schematic and results from experiments that initially confirmed the viability of the PSEC-4 for GPR full

wave acquisitions. A harmonic signal (1 GHz) was the source. Extracting the amplitude of the return harmonic signal waveform from various target position configurations provided the output, Figure 36.b. The next tests used a pulse source signal and attempted to identify the presence of both a steel rebar and pipe target using a mechanically scanned (rolling of radar system) method. Figure 37 shows the two-target pulse-source launch and receive experimental setup with the PSEC-4 WFS-ASIC. Figure 38 shows B-scan results from the test. The PSEC-4 was successful in taking these measurements.

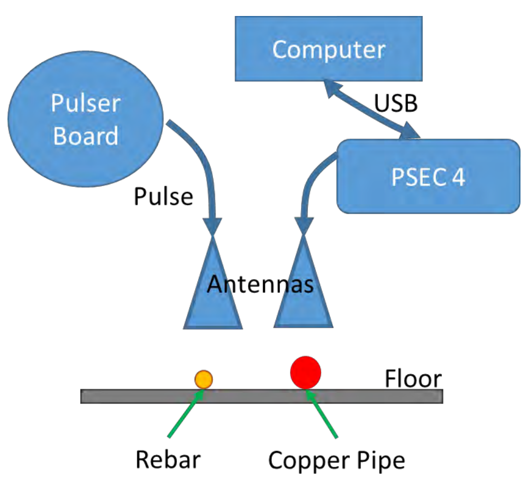


a. **Test Schematic**



b. **Rebar detection with harmonic signal**

Figure 36 Measurement of PSEC-4 performance using harmonic source signals: a. Test schematic, b. Amplitude of detected harmonic signal



a.

b.

Figure 37 Two target pulse launch and receive experimental setup with the PSEC-4 WFS-ASIC: a. experimental schematic, and b. Steel rebar and copper pipe targets

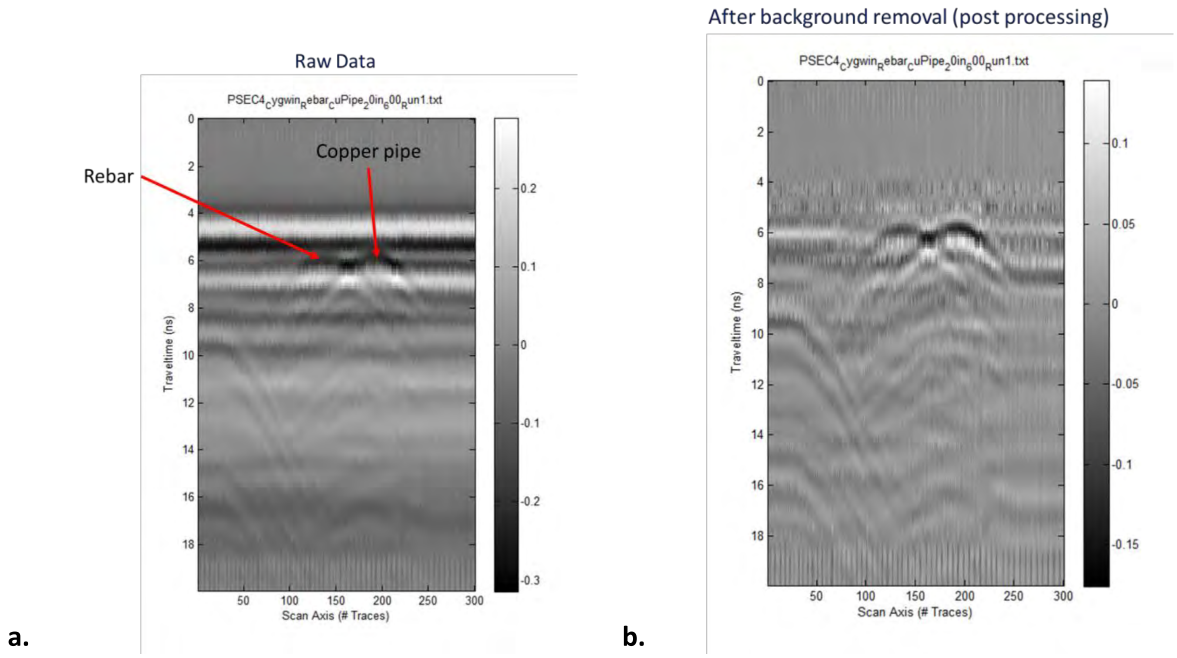


Figure 38 B-scan results from two-target pulse launch and receive tests: a. Raw data, and b. Data post-processed for background removal.

The next set of tests used the PSEC-4 to measure the behavior of a GPR operating in a combined 2-source and 2-receiver antenna configuration, Figure 39 and Figure 40. Typical results appear in Figure 41. The results of the experiments indicate that the PSEC-4 can simultaneously sample and store multiple waveforms.

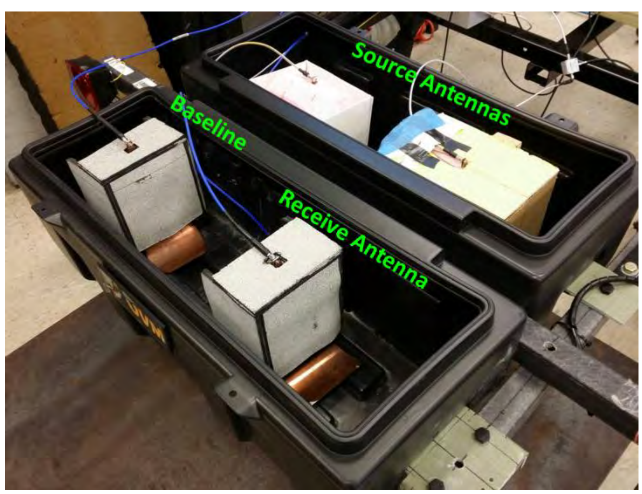


Figure 39 2 source and 2 receive antenna configuration for PSEC-4 system performance study

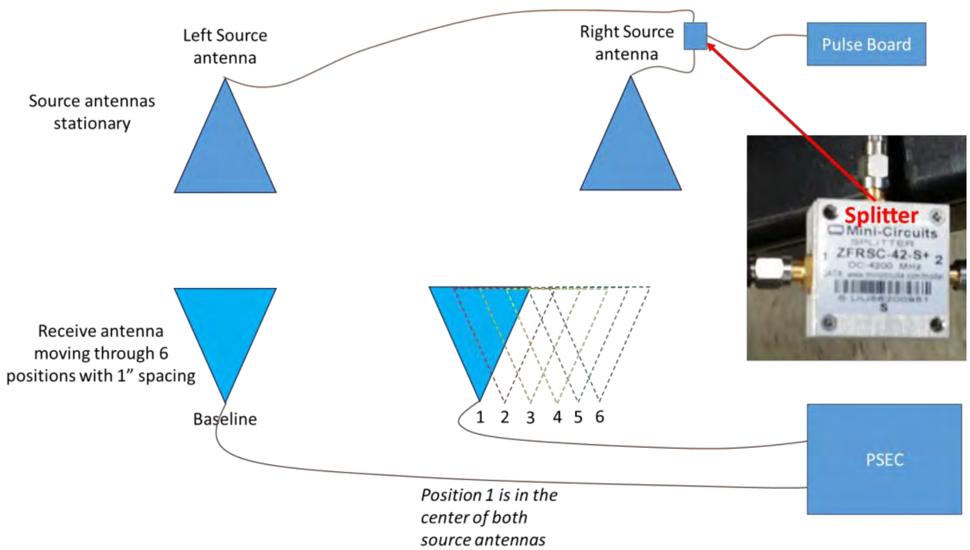


Figure 40 Schematic of 2 source and 2 receive antenna system performance study

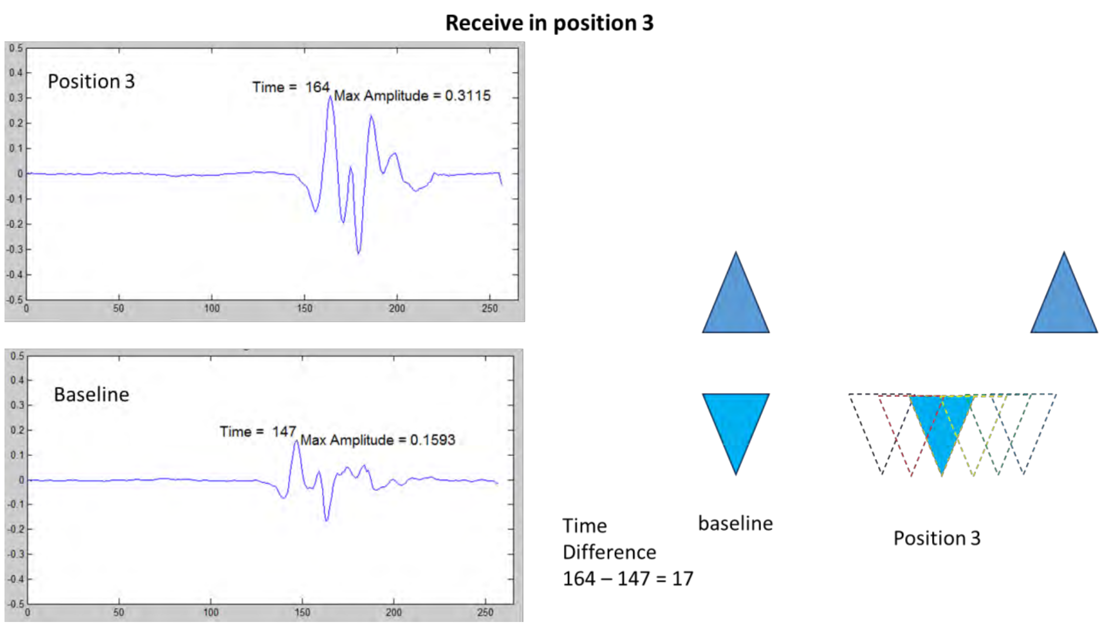


Figure 41 Typical results from 2 source and 2 receive antenna system performance study

4.2.4 Orthogonal Frequency Division Multiplexing with Arbitrary Waveform Generator

A study has been undertaken to use Orthogonal Frequency Division Multiplexing (OFDM) methods with radar signals. The OFDM technique is commonly used in communications, but less so in radar applications. The technique uses multi-tone source signals synthesized with superposed harmonic content at select frequencies, amplitudes and phases to make for efficient demodulation on the receive end for target identification and location. This project

makes use of the AT-N8241A 15 bit 1.25 GHz Arbitrary Waveform Generator with LXI Module to synthesize the source waveforms. Figure 42 shows the instrument setup for the OFDM radar tests and Figure 43 the associated experimental block diagram. Figure 44 shows typical results.

a.  b. 

Figure 42 ODFM Radar test setup: a. close-up of N8241 AWG connections, and b. test instrument suite including AWG and oscilliscope-based spectrum analyzer

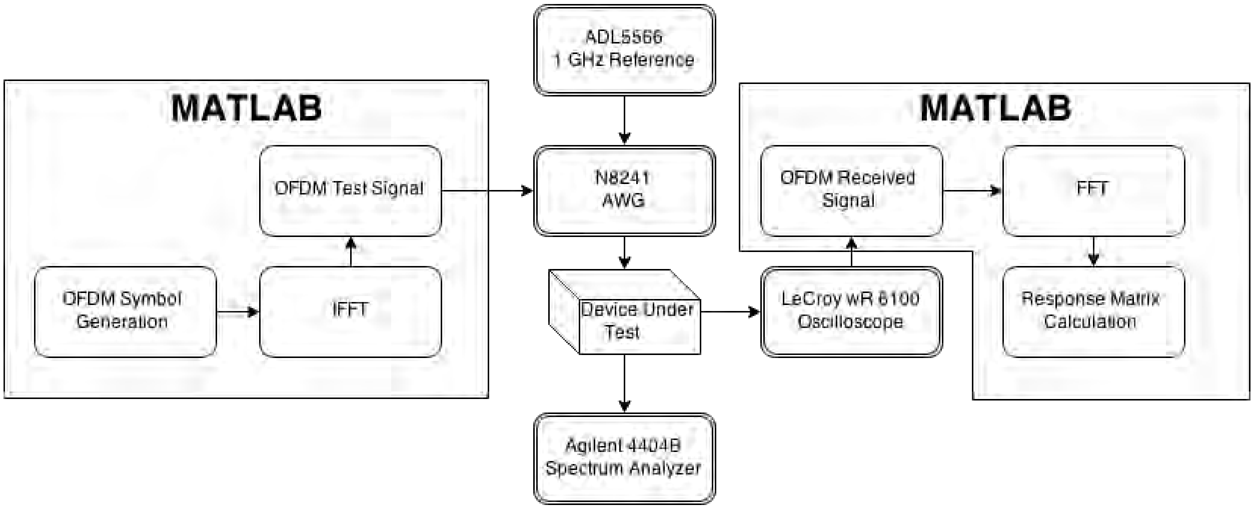


Figure 43 Block diagram of OFDM radar experiment

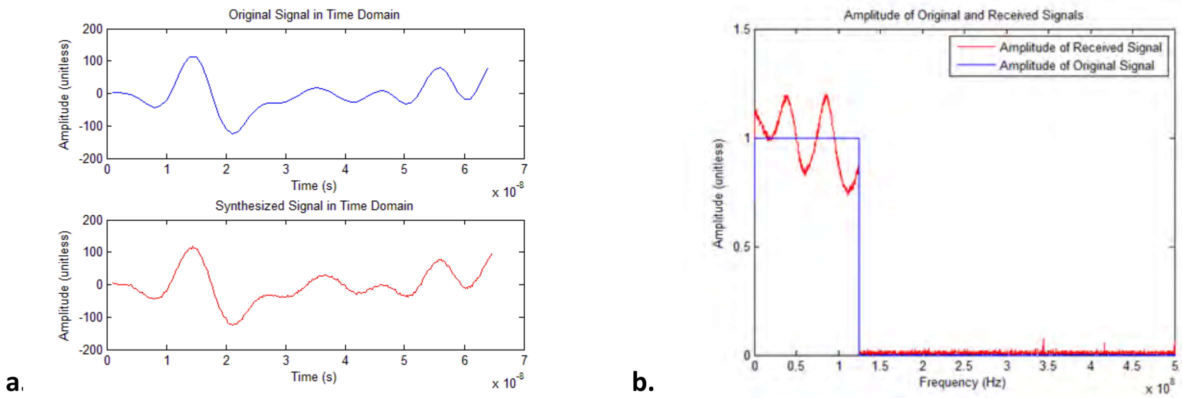
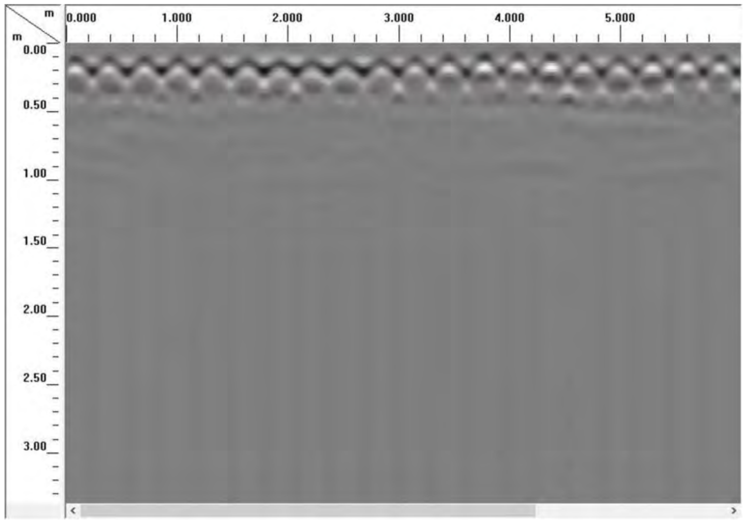


Figure 44 Typical OFDM radar test results: a. Time domain OFDM signal with top trace original signal in time domain from Matlab, and bottom trace synthesized signal from N8241 AWG, and b. Amplitude of original and received signals in the frequency domain.

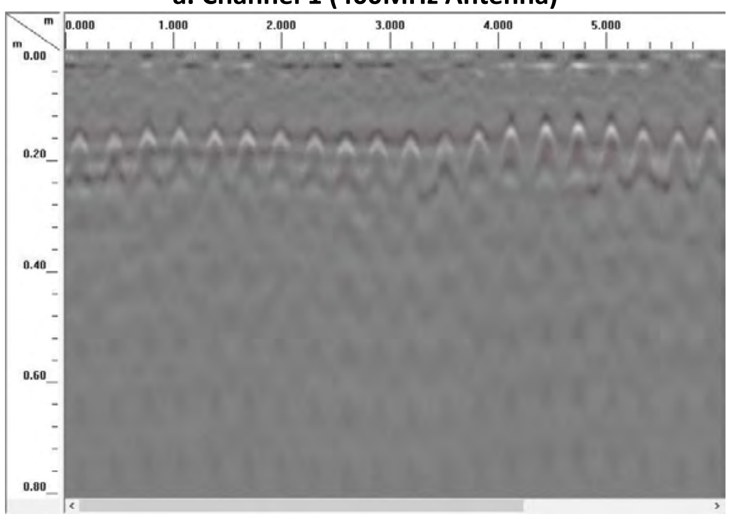
4.2.5 Dual-Band Ground Penetrating Radar

A dual-band GPR system was acquired as an initial step towards building a cognitive GPR system. Tests have been run confirming the viability of the dual-band operation, mostly in the vicinity of the test laboratory (Fleming Museum, University of Vermont). Figure 45 shows the dual-band system on the Fleming Museum sidewalk. Figure 46 shows test results from the dual-band GPR measurements with B-scans taken at a. 400 MHz and b. 1,600 MHz. (Note that the vertical-axis depth scales differ.) Both B-scans show the presence of subsurface steel rebars in the sidewalk. Figure 47 shows the start and stop points of the Fleming Museum dual-band GPR road scan. Figure 48 shows test results from the dual-band GPR measurements with B-scans taken at a. 400 MHz and b. 1,600 MHz. (Note that the vertical-axis depth scales differ.) The 400 MHz antenna shows greater penetration depth but lower resolution than the 1,600 MHz test. Preliminary progress has been made using the Software Development Kit (SDK) from the vendor (GSSI) for control of the operation of the dual channels, ultimately in a cognitive mode.

Figure 45 Dual-band GPR during Fleming Museum sidewalk scan



a. Channel 1 (400MHz Antenna)



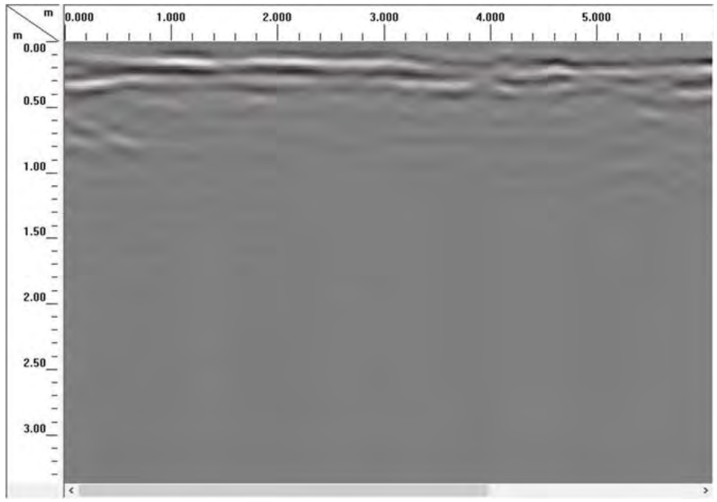
b. Channel 2 (1.6GHz Antenna)

Figure 46 Dual-band GPR test results from Fleming Museum sidewalk scan: a. Channel 1 (400 MHz Antenna), b. Channel 2 (1,600 MHz Antenna)

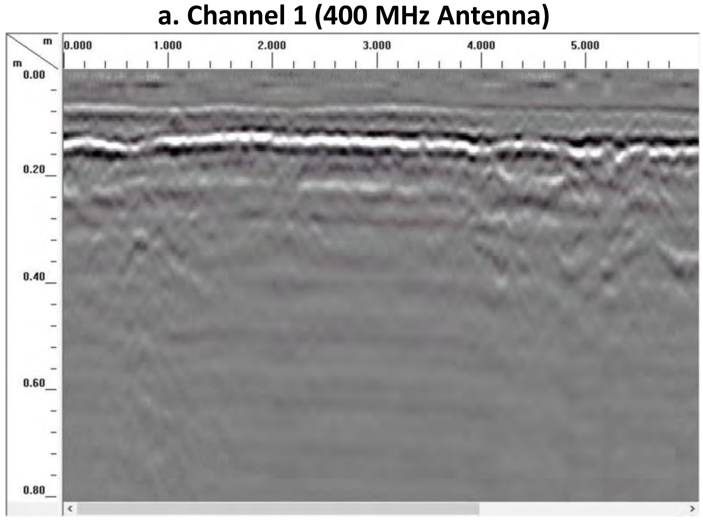
a. Channel 1 (400MHz Antenna)

b. Channel 2 (1.6GHz Antenna)

Figure 47 Dual-band GPR Fleming Museum road scan: a. Start position, b. Stop position



a. Channel 1 (400 MHz Antenna)



b. Channel 2 (1.6 GHz Antenna)

Figure 48 Dual-band GPR test results from Fleming Museum sidewalk scan: a. Channel 1 (400 MHz Antenna), b. Channel 2 (1,600 MHz Antenna)

4.3 Educational and Workforce Enhancement

The equipment to date has been used by the following headcount of UVM graduate and postdoctoral students: MS Electrical Engineering – 3 (1 completed and 2 in progress), MS Mechanical Engineering – 1 (1 completed), PhD Electrical Engineering (1 in progress), and Postdoctoral Researcher 1.

Publications, student theses and presentations to date are listed in the bibliography.

5. Bibliography

Ahmed A, Zhang Y, Venkatachalam A, Burns D, Huston D, Xia T. (2015) “Design of UWB Antenna for Air Coupled Impulse Ground Penetrating Radar Applications,” submitted to IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing

Ahmed A. (2014) “Design and Optimization of UWB Antenna for Air Coupled GPR Applications” M.S. Thesis, Electrical Engineering, University of Vermont

Huston D, Razinger J, Burns D, Xia T. (2015) “Phased Array and Nonlinear Ground Penetrating Radar Development” presented at SPIE Smart Structures/NDE Conference, San Diego, CA, unpublished

Huston D, Burns D, Razinger J, Xia T. (2014) “Concrete Inspection with Phased Array and Nonlinear Penetrating Radar” presented at ASNT NDE/NDT for Highways and Bridges: Structural Materials Technology (SMT), Washington, DC, unpublished

Huston D, Burns D, Venkatachalam A, Zhang Y, Xia T. (2014) “Microwave Concrete Assessment with Phased Array, Nonlinear and Waveform Sampling Methods” presented at ASCE Engineering Mechanics Conference, Hamilton, Ontario, Canada, unpublished

Metwally M. (2014) “OFDM Coupled Compressive Sensing Algorithm for Stepped-Frequency Ground Penetrating Radar” M.S.Thesis, Electrical Engineering, University of Vermont

Metwally M, Esperance N, Xia T. (2015) "Compressive Sampling Coupled OFDM Technique for Testing Continuous Wave Radar," The Journal of Electronic Testing: Theory and Applications (JETTA), Vol. 31, Issue 1, pp. 75-83. Springer, DOI 10.1007/s10836-014-5501-5

Metwally M, Esperance N, Xia T. (2015) "Ground Penetrating Radar Utilizing Compressive Sampling and OFDM Techniques," Accepted by IEEE International Symposium on Circuits and Systems (ISCAS), 2015

Razinger J. (2014) “Performance Evaluation of an Air-Coupled Phased-Array Radar for Near-Field Detection Of Steel” M.S. Thesis, Mechanical Engineering, University of Vermont

Zhang Y, Burns D, Huston D, Xia T. (2015) "Sand Moisture Assessment using Instantaneous Phase Information in Ground Penetrating Radar Data", SPIE Smart Structures/NDE Conference 2015, publication pending